Theories of the Initial State

Chris Smeenk

University of Western Ontario
Department of Philosophy
Rotman Institute

Aims for Cosmological Theories

- Indifference / Independence
  - Dynamics sufficient to produce "order out of chaos"
  - Equilibrium explanation
- Specific Initial State
  - Theoretical principles, special postulate, or "brute fact"

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Eliminating Initial Conditions

[We must] find some way of eliminating the need for an initial condition to be specified. Only then will the universe be subject to the rule of theory. ... This provides us with a criterion so compelling that the theory of the universe which best conforms us to it is almost certain to be right.
(Sciama 1959)

Dennis Sciama

Defending steady state theory...
replace with steady state eternal inflation?

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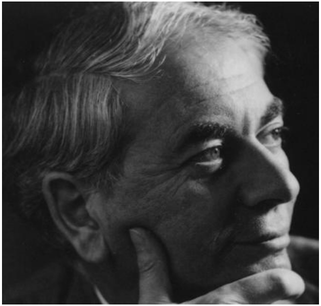

Dennis Sciama

Defending steady state theory... replace with steady state eternal inflation?

Outline

- An Initial State?
- Theories of the Initial State
- Inflationary Dialectic
- Eternal Inflation

Does the universe have an “initial state”?
… or, better: Is the universe finite to the past?

Singularities

FLRW Models

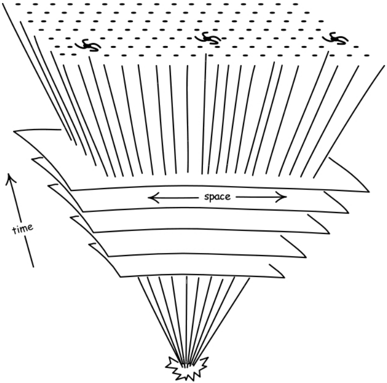

Image Credit: John Norton

- Einstein's field equations reduce to two equations for $R(t)$
- Extrapolating backwards: $R(t) \rightarrow 0$ and $\rho(t) \rightarrow \infty$ within finite time T

Singularities

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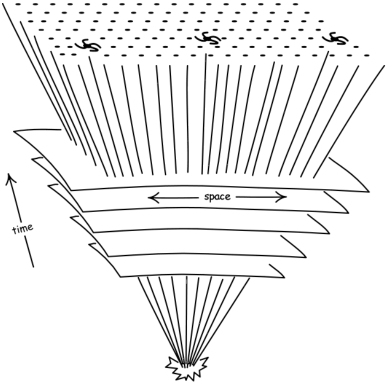

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Generalizing:

- Gravity is attractive $\rightarrow$ positive energy density leads to geodesic convergence, conjugate points
- Maximal curves: geodesics with no conjugate points

Given a spacetime with the following properties (Wald, Thm 9.5.4):

1. *Curvature:* (a) $R_{ab}\xi^a\xi^b \geq 0$ for all timelike or null ξ^a. (Follows from Einstein's field eqns. and strong energy condition.)
   (b) Timelike and null generic conditions hold.
2. *Causal Structure:* There are no closed timelike curves.
3. *Cosmology:* There is a point such that the expansion of a congruence of past- (future-) directed null geodesics is negative.

Conclusion

The spacetime has at least one incomplete geodesic (*singular* spacetime).

Status of the Theorems?

To what extent do the assumptions depend on classical GR?

1. *Curvature:* Weak dependence on EFE
   ... but energy conditions fail! (e.g., strong energy condition violated by inflation and dark energy)
2. *Causal Structure:* Constraints on spacetime geometry, more general than EFE.
3. *Cosmology:* Modest: expansion of null geodesics from present time becomes negative more recently than decoupling.

Extending Singularity Theorems?

- Singularity theorems for Inflation
  - Borde, Guth, Vilenkin (2003): consider local expansion rate H for a congruence of geodesics. If average expansion $H \geq H_{lb} > 0 \rightarrow$ upper bound on the integral of the expansion rate, past incomplete curve. *No energy conditions assumed.*
  - But doesn't imply curvature singularity. Better: "boundary" theorem. (Cf. Aguirre 0712.0571; Vilenkin 2013)

Extending Singularity Theorems?

- Quantum Gravity Effects
  - Loop Quantum Cosmology (Bojowald, Ashtekar et al.): curvature bounded above, dynamical evolution extends through (classical) singularity
  - String theory: some singularities may be resolved by extra degrees of freedom
  - Cyclic cosmologies: argue for continuation through singularity in higher dimensional spaces

Does the universe have an "initial state" / is it finite to the past?

- Answer depends on:
  (1) status of energy conditions,
  (2) implications of more general "singularity" theorems,
  (3) quantum gravity effects at Planck scale

Responses to Singularities

- Nature abhors a singularity? (cf. Earman 1995)
  - Failure of determinism ... not in FLRW models → cosmic censorship
  - Break-down of GR ... singularities not localized regions, no region *within* classical spacetime where GR fails
- Boundary of domain of applicability
  - Quantum effects important in strong curvature regime

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Handling the Initial State

- Dynamical Approaches
  - V 1.0: "wash away" dependence on ICs (old rhetoric)
  - V 2.0: multiverse leads to equilibrium state, predictions independent of ICs (new rhetoric)
- Postulate / Constraint on Initial State
  - Past Hypothesis
  - Quantum Cosmology

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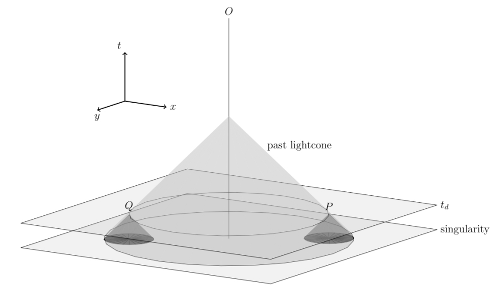
Old Rhetoric: Inflation and Initial Conditions

Due to causal structure (horizon) and dynamics (flatness), standard cosmological model apparently requires pre-established harmony and finely-tuned initial value of Ω ...

Horizon / Smoothness Problem



Flatness Problem

Density parameter $\Omega = \frac{\rho_c}{\rho}$ evolves away from 1 (flat model) with expansion ($R(t)$ =: scale factor):

$$\frac{|\Omega - 1|}{\Omega} \propto R^2(t) \tag{1}$$

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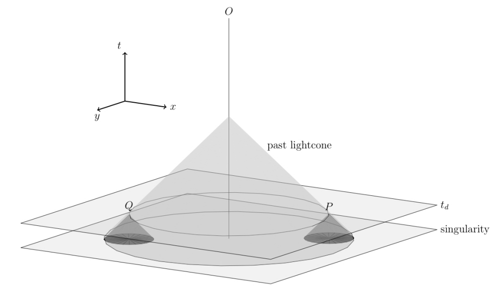

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... Solved by Inflation?

- Horizon distance stretched by a factor of $e^{\mathcal{N}}$ for $\mathcal{N}$ e-foldings, during inflation dynamics drives $\Omega \to 1$
- Uniform, flat patch as the "generic" post-inflationary state, for sufficiently large $\mathcal{N}$

Penrose Objection

- Assume that measure is invariant under dynamics during inflationary stage (e.g., μ_{GHS}).
- Then pre-inflationary state must be *less probable* than the post-inflationary state. Replace original fine-tuning with fine-tuning of initial state of inflaton field.

(See Penrose 2004 for recent formulation.)

Question

Is the dynamics during inflation measure-preserving? (Unitary?) (Cf. Kofman et al. 2002, Hollands and Wald 2002)

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Retrodicting Inflation?

- Given present state, "retrodict" generic (according to μ_{GHS}) trajectories $\longrightarrow$ *nothing like* observed history. Growing inhomogeneities, no inflationary phase, etc.
- Past Hypothesis: constraint on initial conditions of inflaton field. (Conflict between use of PH and old rhetoric.)
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Aside: Inflation "... as a theory of structure formation"

...[T]hese problems [related to initial conditions] can no longer be regarded as the strongest motivation for inflationary cosmology because it is not at all clear that they could ever be used to falsify inflation. [...] By contrast to inflation as a theory of initial conditions, the model of inflation as a possible origin of structure in the Universe is a powerfully predictive one. Different inflation models typically lead to different predictions for observed structures, and observations can discriminate strongly between them. ... *Inflation as the origin of structure is therefore very much a proper science of prediction and observation.* (Liddle and Lyth 2000, p. 5; my emphasis)

Aside: Inflation "... as a theory of structure formation"

- Law-like connections between properties of inflaton and density perturbations, etc.
- Challenges: (1) *independent* measurements of properties of the inflaton field; (2) degree of overdetermination of details of inflation

Status of the Past Hypothesis

What is the status of the PH compared to other basic principles or assumptions in physical theories?

Laws vs. Initial Conditions?

Mill-Ramsey-Lewis Approach

Capture some body of physical knowledge in a deductive system.

Laws = axioms in the "best" such systemization, one that maximizes strength (large number of derived consequences) and simplicity (small number of basic principles).

Consequence

PH (plausibly) comes out as a *law* given this definition. Evidence for PH based on systematic role.

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New Approach: Eternal Inflation

Argument that inflation is "generically eternal," leads to multiverse from initial fluctuation.

Replace question regarding "unnaturalness" of ICs for inflation with: "What does a typical observer in the multiverse see?"

Eternal Inflation

Probability for inflaton field to fluctuate up from de Sitter vacuum to appropriate initial state for eternal inflation (Carroll and Chen 2004):

$$P \approx 10^{-10^{10^{56}}}$$

Footnote: "We suspect that this may be smallest positive number in the history of physics..." [... only has to be non-zero]

Western

Refining the Question?

From unnaturalness of ICs for inflation → predictions in EI:

- Shift in understanding equilibrium state for quantum gravity?
- Bubble nucleation / account of spontaneous fluctuation?
- Status of the PH and time's arrow in EI? Does granting PH undermine this further step?

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Predictions in EI

In an eternally inflating universe, anything that can happen will happen; in fact, it will happen an infinite number of times. Thus, the question of what is possible becomes trivial — anything is possible, unless it violates some absolute conservation law. To extract predictions from the theory, we must therefore learn to distinguish the probable from the improbable. (Guth 2007)

Obstacles

- Measure Problem
- ... even granting that a measure is found:
  - justification of "principle of mediocrity" / typicality?
  - anthropic reasoning?

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Doomsday Argument (Gott 1994)

- Evaluate prediction of the total number of humans N based on our birth rank r
- Assume that we have "typical" r, motivating $Pr(r|N) = 1/N$. Further assume, for a constant k, the vague priors:

$$Pr(N) = k/N, Pr(r) = k/r$$

Application of Bayes's theorem leads to posterior:

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Problems with Typicality

- Doomsday Argument: Learn too much!
- How to describe real ignorance?
  - Norton (2010): uniform probability distribution does not represent "ignorance" or "neutral evidence," advocates alternative inductive logic
  - Imprecise probabilities in Bayesian approach (Joyce 2010, Benétreau-Dupin 2013)

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Anthropic Reasoning

- Consider observational bounds on a parameter: $\alpha \in \Delta$, call S the region satisfying this constraint. *Given* regularized measure μ^*.
- Further ingredient: "anthropic subset" $\mathcal{A}$, parameter values $\alpha \in \Delta'$ "compatible with life"

$$Pr(S) = \frac{\mu^*(S)}{\mu^*(\mathcal{A})}$$

- Evaluate a theory based only on anthropic subset, not disconfirmed by observer-less pocket universes with $\alpha \notin \Delta$
- Problems: What is the extent of the anthropic subset $\mathcal{A}$, e.g. in regions of parameter space far from observed values? Reference class dependence? ...

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Boltzmann Brains

- Theory with finite maximum entropy, S_{max}.
- Consider collection of physical states = current brain state of some observer.
- "Typical" member of this collection will be a Boltzmann brain, given relative probabilities of small vs. large fluctuations away from S_{max}.
- Conclusion: This theory is falsified!
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A theory is ESU if accepting the theory undermines the very evidence used to support the theory.

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